

# Contents

*Preface* xv

## Part 1 Basics 2

### 1 Introduction to Mechanical Engineering Design 3

- 1-1** Design 4
- 1-2** Mechanical Engineering Design 5
- 1-3** Phases and Interactions of the Design Process 5
- 1-4** Design Tools and Resources 8
- 1-5** The Design Engineer's Professional Responsibilities 10
- 1-6** Standards and Codes 12
- 1-7** Economics 13
- 1-8** Safety and Product Liability 15
- 1-9** Stress and Strength 16
- 1-10** Uncertainty 16
- 1-11** Design Factor and Factor of Safety 18
- 1-12** Reliability and Probability of Failure 20
- 1-13** Relating the Design Factor to Reliability 24
- 1-14** Dimensions and Tolerances 27
- 1-15** Units 31
- 1-16** Calculations and Significant Figures 32
- 1-17** Design Topic Interdependencies 33
- 1-18** Power Transmission Case Study Specifications 34
- Problems** 36

### 2 Materials 41

- 2-1** Material Strength and Stiffness 42
- 2-2** The Statistical Significance of Material Properties 46
- 2-3** Strength and Cold Work 49
- 2-4** Hardness 52

- 2-5** Impact Properties 53
- 2-6** Temperature Effects 54
- 2-7** Numbering Systems 56
- 2-8** Sand Casting 57
- 2-9** Shell Molding 57
- 2-10** Investment Casting 58
- 2-11** Powder-Metallurgy Process 58
- 2-12** Hot-Working Processes 58
- 2-13** Cold-Working Processes 59
- 2-14** The Heat Treatment of Steel 60
- 2-15** Alloy Steels 63
- 2-16** Corrosion-Resistant Steels 64
- 2-17** Casting Materials 65
- 2-18** Nonferrous Metals 67
- 2-19** Plastics 70
- 2-20** Composite Materials 71
- 2-21** Materials Selection 72
- Problems** 79

### 3 Load and Stress Analysis 85

- 3-1** Equilibrium and Free-Body Diagrams 86
- 3-2** Shear Force and Bending Moments in Beams 89
- 3-3** Singularity Functions 91
- 3-4** Stress 93
- 3-5** Cartesian Stress Components 93
- 3-6** Mohr's Circle for Plane Stress 94
- 3-7** General Three-Dimensional Stress 100
- 3-8** Elastic Strain 101
- 3-9** Uniformly Distributed Stresses 102
- 3-10** Normal Stresses for Beams in Bending 103
- 3-11** Shear Stresses for Beams in Bending 108
- 3-12** Torsion 115
- 3-13** Stress Concentration 124

|               |   |     |
|---------------|---|-----|
| <b>3-14</b>   | Stresses in Pressurized Cylinders                                   | 127 |
| <b>3-15</b>   | Stresses in Rotating Rings  | 129 |
| <b>3-16</b>   | Press and Shrink Fits   | 130 |
| <b>3-17</b>   | Temperature Effects   | 131 |
| <b>3-18</b>   | Curved Beams in Bending   | 132 |
| <b>3-19</b>   | Contact Stresses  | 136 |
| <b>3-20</b>   | Summary   | 140 |
|               | <b>Problems</b>   | 141 |
| <b>4</b>      | <b>Deflection and Stiffness</b>                                     | 161 |
| <b>4-1</b>    | Spring Rates  | 162 |
| <b>4-2</b>    | Tension, Compression, and Torsion                                   | 163 |
| <b>4-3</b>    | Deflection Due to Bending   | 164 |
| <b>4-4</b>    | Beam Deflection Methods   | 166 |
| <b>4-5</b>    | Beam Deflections by Superposition                                   | 167 |
| <b>4-6</b>    | Beam Deflections by Singularity Functions                           | 170 |
| <b>4-7</b>    | Strain Energy   | 176 |
| <b>4-8</b>    | Castigliano's Theorem   | 178 |
| <b>4-9</b>    | Deflection of Curved Members  | 183 |
| <b>4-10</b>   | Statically Indeterminate Problems                                   | 189 |
| <b>4-11</b>   | Compression Members—General   | 195 |
| <b>4-12</b>   | Long Columns with Central Loading                                   | 195 |
| <b>4-13</b>   | Intermediate-Length Columns with Central Loading                    | 198 |
| <b>4-14</b>   | Columns with Eccentric Loading                                      | 198 |
| <b>4-15</b>   | Struts or Short Compression Members                                 | 200 |
| <b>4-16</b>   | Elastic Stability   | 204 |
| <b>4-17</b>   | Shock and Impact  | 205 |
|               | <b>Problems</b>   | 206 |
| <b>Part 2</b> | <b>Failure Prevention</b>   | 226 |
| <b>5</b>      | <b>Failures Resulting from Static Loading</b>                       | 227 |
| <b>5-1</b>    | Static Strength   | 230 |
| <b>5-2</b>    | Stress Concentration  | 231 |
| <b>5-3</b>    | Failure Theories  | 233 |
| <b>5-4</b>    | Maximum-Shear-Stress Theory for Ductile Materials                   | 233 |
| <b>5-5</b>    | Distortion-Energy Theory for Ductile Materials                      | 235 |
| <b>5-6</b>    | Coulomb-Mohr Theory for Ductile Materials                           | 242 |
| <b>5-7</b>    | Failure of Ductile Materials Summary                                | 245 |
| <b>5-8</b>    | Maximum-Normal-Stress Theory for Brittle Materials                  | 249 |
| <b>5-9</b>    | Modifications of the Mohr Theory for Brittle Materials              | 249 |
| <b>5-10</b>   | Failure of Brittle Materials Summary                                | 252 |
| <b>5-11</b>   | Selection of Failure Criteria                                       | 252 |
| <b>5-12</b>   | Introduction to Fracture Mechanics                                  | 253 |
| <b>5-13</b>   | Important Design Equations  | 262 |
|               | <b>Problems</b>   | 264 |
| <b>6</b>      | <b>Fatigue Failure Resulting from Variable Loading</b>              | 273 |
| <b>6-1</b>    | Introduction to Fatigue in Metals                                   | 274 |
| <b>6-2</b>    | Approach to Fatigue Failure in Analysis and Design                  | 280 |
| <b>6-3</b>    | Fatigue-Life Methods  | 281 |
| <b>6-4</b>    | The Stress-Life Method  | 281 |
| <b>6-5</b>    | The Strain-Life Method  | 284 |
| <b>6-6</b>    | The Linear-Elastic Fracture Mechanics Method                        | 286 |
| <b>6-7</b>    | The Endurance Limit   | 290 |
| <b>6-8</b>    | Fatigue Strength  | 291 |
| <b>6-9</b>    | Endurance Limit Modifying Factors                                   | 294 |
| <b>6-10</b>   | Stress Concentration and Notch Sensitivity                          | 303 |
| <b>6-11</b>   | Characterizing Fluctuating Stresses                                 | 308 |
| <b>6-12</b>   | Fatigue Failure Criteria for Fluctuating Stress                     | 311 |
| <b>6-13</b>   | Torsional Fatigue Strength under Fluctuating Stresses               | 325 |
| <b>6-14</b>   | Combinations of Loading Modes                                       | 325 |
| <b>6-15</b>   | Varying, Fluctuating Stresses; Cumulative Fatigue Damage            | 329 |
| <b>6-16</b>   | Surface Fatigue Strength  | 335 |
| <b>6-17</b>   | Road Maps and Important Design Equations for the Stress-Life Method | 338 |
|               | <b>Problems</b>   | 341 |

**Part 3 Design of Mechanical Elements** 350**7 Shafts and Shaft Components** 351

**7-1** Introduction 352  
**7-2** Shaft Materials 352  
**7-3** Shaft Layout 353  
**7-4** Shaft Design for Stress 358  
**7-5** Deflection Considerations 371  
**7-6** Critical Speeds for Shafts 375  
**7-7** Miscellaneous Shaft Components 380  
**7-8** Limits and Fits 387  
**Problems** 392

**8 Screws, Fasteners, and the Design of Nonpermanent Joints** 401

**8-1** Thread Standards and Definitions 402  
**8-2** The Mechanics of Power Screws 406  
**8-3** Threaded Fasteners 414  
**8-4** Joints—Fastener Stiffness 416  
**8-5** Joints—Member Stiffness 419  
**8-6** Bolt Strength 424  
**8-7** Tension Joints—The External Load 427  
**8-8** Relating Bolt Torque to Bolt Tension 429  
**8-9** Statically Loaded Tension Joint with Preload 432  
**8-10** Gasketed Joints 436  
**8-11** Fatigue Loading of Tension Joints 436  
**8-12** Bolted and Riveted Joints Loaded in Shear 443  
**Problems** 451

**9 Welding, Bonding, and the Design of Permanent Joints** 467

**9-1** Welding Symbols 468  
**9-2** Butt and Fillet Welds 470  
**9-3** Stresses in Welded Joints in Torsion 474  
**9-4** Stresses in Welded Joints in Bending 479

**9-5** The Strength of Welded Joints 481  
**9-6** Static Loading 484  
**9-7** Fatigue Loading 488  
**9-8** Resistance Welding 490  
**9-9** Adhesive Bonding 490  
**Problems** 499

**10 Mechanical Springs** 509

**10-1** Stresses in Helical Springs 510  
**10-2** The Curvature Effect 511  
**10-3** Deflection of Helical Springs 512  
**10-4** Compression Springs 512  
**10-5** Stability 514  
**10-6** Spring Materials 515  
**10-7** Helical Compression Spring Design for Static Service 520  
**10-8** Critical Frequency of Helical Springs 526  
**10-9** Fatigue Loading of Helical Compression Springs 528  
**10-10** Helical Compression Spring Design for Fatigue Loading 531  
**10-11** Extension Springs 534  
**10-12** Helical Coil Torsion Springs 542  
**10-13** Belleville Springs 549  
**10-14** Miscellaneous Springs 550  
**10-15** Summary 552  
**Problems** 552

**11 Rolling-Contact Bearings** 561

**11-1** Bearing Types 562  
**11-2** Bearing Life 565  
**11-3** Bearing Load Life at Rated Reliability 566  
**11-4** Reliability versus Life—The Weibull Distribution 568  
**11-5** Relating Load, Life, and Reliability 569  
**11-6** Combined Radial and Thrust Loading 571  
**11-7** Variable Loading 577  
**11-8** Selection of Ball and Cylindrical Roller Bearings 580  
**11-9** Selection of Tapered Roller Bearings 583  
**11-10** Design Assessment for Selected Rolling-Contact Bearings 592

|              |  |                 |   |
|--------------|--|-----------------|---|
| <b>11-11</b> | Lubrication 596  | <b>13-17</b>    | Force Analysis—Worm Gearing 706                       |
| <b>11-12</b> | Mounting and Enclosure 597                             | <b>Problems</b> | 712   |
|              | Problems 601   |                 |   |
| <b>12</b>    | <b>Lubrication and Journal Bearings</b> 609            | <b>14</b>       | <b>Spur and Helical Gears</b> 725                     |
| <b>12-1</b>  | Types of Lubrication 610                               | <b>14-1</b>     | The Lewis Bending Equation 726                        |
| <b>12-2</b>  | Viscosity 611  | <b>14-2</b>     | Surface Durability 735                                |
| <b>12-3</b>  | Petroff's Equation 613                                 | <b>14-3</b>     | AGMA Stress Equations 737                             |
| <b>12-4</b>  | Stable Lubrication 615                                 | <b>14-4</b>     | AGMA Strength Equations 739                           |
| <b>12-5</b>  | Thick-Film Lubrication 616                             | <b>14-5</b>     | Geometry Factors $I$ and $J$ ( $Z_I$ and $Y_J$ ) 743  |
| <b>12-6</b>  | Hydrodynamic Theory 617                                | <b>14-6</b>     | The Elastic Coefficient $C_p$ ( $Z_E$ ) 748           |
| <b>12-7</b>  | Design Considerations 621                              | <b>14-7</b>     | Dynamic Factor $K_v$ 748                              |
| <b>12-8</b>  | The Relations of the Variables 623                     | <b>14-8</b>     | Overload Factor $K_o$ 750                             |
| <b>12-9</b>  | Steady-State Conditions in Self-Contained Bearings 637 | <b>14-9</b>     | Surface Condition Factor $C_f$ ( $Z_R$ ) 750          |
| <b>12-10</b> | Clearance 640  | <b>14-10</b>    | Size Factor $K_s$ 751                                 |
| <b>12-11</b> | Pressure-Fed Bearings 642                              | <b>14-11</b>    | Load-Distribution Factor $K_m$ ( $K_H$ ) 751          |
| <b>12-12</b> | Loads and Materials 648                                | <b>14-12</b>    | Hardness-Ratio Factor $C_H$ ( $Z_W$ ) 753             |
| <b>12-13</b> | Bearing Types 650                                      | <b>14-13</b>    | Stress-Cycle Factors $Y_N$ and $Z_N$ 754              |
| <b>12-14</b> | Thrust Bearings 651                                    | <b>14-14</b>    | Reliability Factor $K_R$ ( $Y_Z$ ) 755                |
| <b>12-15</b> | Boundary-Lubricated Bearings 652                       | <b>14-15</b>    | Temperature Factor $K_T$ ( $Y_\theta$ ) 756           |
|              | Problems 660   | <b>14-16</b>    | Rim-Thickness Factor $K_B$ 756                        |
| <b>13</b>    | <b>Gears—General</b> 665                               | <b>14-17</b>    | Safety Factors $S_F$ and $S_H$ 757                    |
| <b>13-1</b>  | Types of Gears 666                                     | <b>14-18</b>    | Analysis 757  |
| <b>13-2</b>  | Nomenclature 667                                       | <b>14-19</b>    | Design of a Gear Mesh 767                             |
| <b>13-3</b>  | Conjugate Action 669                                   |                 | Problems 772  |
| <b>13-4</b>  | Involute Properties 670                                | <b>15</b>       | <b>Bevel and Worm Gears</b> 777                       |
| <b>13-5</b>  | Fundamentals 670                                       | <b>15-1</b>     | Bevel Gearing—General 778                             |
| <b>13-6</b>  | Contact Ratio 676                                      | <b>15-2</b>     | Bevel-Gear Stresses and Strengths 780                 |
| <b>13-7</b>  | Interference 677                                       | <b>15-3</b>     | AGMA Equation Factors 783                             |
| <b>13-8</b>  | The Forming of Gear Teeth 679                          | <b>15-4</b>     | Straight-Bevel Gear Analysis 795                      |
| <b>13-9</b>  | Straight Bevel Gears 682                               | <b>15-5</b>     | Design of a Straight-Bevel Gear Mesh 798              |
| <b>13-10</b> | Parallel Helical Gears 683                             | <b>15-6</b>     | Worm Gearing—AGMA Equation 801                        |
| <b>13-11</b> | Worm Gears 687   | <b>15-7</b>     | Worm-Gear Analysis 805                                |
| <b>13-12</b> | Tooth Systems 688                                      | <b>15-8</b>     | Designing a Worm-Gear Mesh 809                        |
| <b>13-13</b> | Gear Trains 690  | <b>15-9</b>     | Buckingham Wear Load 812                              |
| <b>13-14</b> | Force Analysis—Spur Gearing 697                        |                 | Problems 813  |
| <b>13-15</b> | Force Analysis—Bevel Gearing 701                       | <b>16</b>       | <b>Clutches, Brakes, Couplings, and Flywheels</b> 817 |
| <b>13-16</b> | Force Analysis—Helical Gearing 704                     | <b>16-1</b>     | Static Analysis of Clutches and Brakes 819            |
|              |  | <b>16-2</b>     | Internal Expanding Rim Clutches and Brakes 824        |

|              |  |     |
|--------------|--|-----|
| <b>16-3</b>  | External Contracting Rim Clutches and Brakes | 832 |
| <b>16-4</b>  | Band-Type Clutches and Brakes                | 836 |
| <b>16-5</b>  | Frictional-Contact Axial Clutches            | 837 |
| <b>16-6</b>  | Disk Brakes                                  | 841 |
| <b>16-7</b>  | Cone Clutches and Brakes                     | 845 |
| <b>16-8</b>  | Energy Considerations                        | 848 |
| <b>16-9</b>  | Temperature Rise                             | 849 |
| <b>16-10</b> | Friction Materials                           | 853 |
| <b>16-11</b> | Miscellaneous Clutches and Couplings         | 856 |
| <b>16-12</b> | Flywheels                                    | 858 |
|              | Problems                                     | 863 |

## **17 Flexible Mechanical Elements** 871

|             |                             |     |
|-------------|-----------------------------|-----|
| <b>17-1</b> | Belts                       | 872 |
| <b>17-2</b> | Flat- and Round-Belt Drives | 875 |
| <b>17-3</b> | V Belts                     | 890 |
| <b>17-4</b> | Timing Belts                | 898 |
| <b>17-5</b> | Roller Chain                | 899 |
| <b>17-6</b> | Wire Rope                   | 908 |
| <b>17-7</b> | Flexible Shafts             | 916 |
|             | Problems                    | 917 |

## **18 Power Transmission Case Study** 925

|              |  |     |
|--------------|--|-----|
| <b>18-1</b>  | Design Sequence for Power Transmission | 927 |
| <b>18-2</b>  | Power and Torque Requirements          | 928 |
| <b>18-3</b>  | Gear Specification                     | 928 |
| <b>18-4</b>  | Shaft Layout                           | 935 |
| <b>18-5</b>  | Force Analysis                         | 937 |
| <b>18-6</b>  | Shaft Material Selection               | 937 |
| <b>18-7</b>  | Shaft Design for Stress                | 938 |
| <b>18-8</b>  | Shaft Design for Deflection            | 938 |
| <b>18-9</b>  | Bearing Selection                      | 939 |
| <b>18-10</b> | Key and Retaining Ring Selection       | 940 |
| <b>18-11</b> | Final Analysis                         | 943 |
|              | Problems                               | 943 |

## **Part 4 Special Topics** 944

|              |                                     |     |
|--------------|-------------------------------------|-----|
| <b>19</b>    | <b>Finite-Element Analysis</b>      | 945 |
| <b>19-1</b>  | The Finite-Element Method           | 947 |
| <b>19-2</b>  | Element Geometries                  | 949 |
| <b>19-3</b>  | The Finite-Element Solution Process | 951 |
| <b>19-4</b>  | Mesh Generation                     | 954 |
| <b>19-5</b>  | Load Application                    | 956 |
| <b>19-6</b>  | Boundary Conditions                 | 957 |
| <b>19-7</b>  | Modeling Techniques                 | 958 |
| <b>19-8</b>  | Thermal Stresses                    | 961 |
| <b>19-9</b>  | Critical Buckling Load              | 961 |
| <b>19-10</b> | Vibration Analysis                  | 963 |
| <b>19-11</b> | Summary                             | 964 |
|              | Problems                            | 966 |

## **20 Geometric Dimensioning and Tolerancing** 969

|             |  |      |
|-------------|--|------|
| <b>20-1</b> | Dimensioning and Tolerancing Systems                 | 970  |
| <b>20-2</b> | Definition of Geometric Dimensioning and Tolerancing | 971  |
| <b>20-3</b> | Datums   | 976  |
| <b>20-4</b> | Controlling Geometric Tolerances                     | 981  |
| <b>20-5</b> | Geometric Characteristic Definitions                 | 985  |
| <b>20-6</b> | Material Condition Modifiers                         | 994  |
| <b>20-7</b> | Practical Implementation                             | 996  |
| <b>20-8</b> | GD&T in CAD Models                                   | 1001 |
| <b>20-9</b> | Glossary of GD&T Terms                               | 1002 |
|             | Problems   | 1005 |

## **Appendices**

|          |                                     |      |
|----------|-------------------------------------|------|
| <b>A</b> | <b>Useful Tables</b>                | 1011 |
| <b>B</b> | <b>Answers to Selected Problems</b> | 1067 |